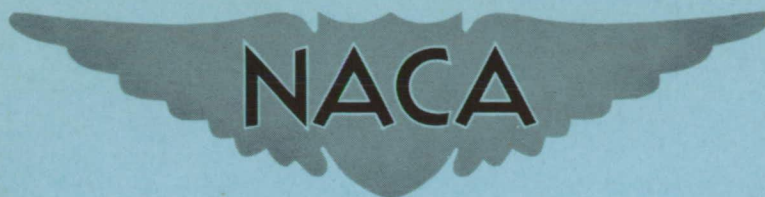


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RESEARCH MEMORANDUM

INFLUENCE OF EXTERNAL VARIABLES ON SMOKING OF

BENZENE FLAMES

By Thomas P. Clark

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

Premixed benzene-air flames were burned under a variety of conditions to determine the effect of the conditions on the smoking properties of the flames. Variations in initial gas temperature, fuel-flow rate, flame length, secondary-air-flow rate, and burner-tube diameter were studied. Fuel-air ratios were measured both at the appearance of the first evidence of carbon formation in the flame, and at the point where smoke issued from the flame. Of all the variables studied, temperature alone affected the fuel-air ratio at which the first evidence of carbon formation was visible in the flame.

A critical fuel-air-ratio limit of approximately 164 percent of stoichiometric was discovered below which no smoke was formed by the flame regardless of the conditions existing in the gas surrounding the flame. At fuel-air ratios above 164 percent of stoichiometric, the smoking tendencies of the flame became very dependent on the conditions in the gas surrounding the flame. In general, all variations which tended to replace the exhaust gases around the outer cone with air or to increase the diffusion of oxygen into the outer cone enhanced the smoke-burning properties and decreased the smoking tendencies of the flame.

INTRODUCTION

This report covers work on the NACA Lewis laboratory study of the combustion of smoke in flames. A previous report was concerned with the burning of smoke supplied from a source outside the flame (reference 1). The experimentation discussed in this report was performed to determine how the smoking properties of a given fuel are modified by changes in several of the variables associated with the burning of the fuel in a combustion chamber. It is of interest to know how these variables affect the initial formation and assimilation of smoke in a flame, for if smoke formation could be controlled in the primary flame reaction zone of a combustion chamber, the problem of burning smoke in the later stages of the combustion process would not exist.

The experiments were performed on a laboratory scale apparatus with a premixed benzene-air laminar flame. Variations in initial mixture temperature, fuel-flow rate, fuel-air ratio, and secondary-air-flow rate were studied. The effect of burning the mixture without secondary air in contact with the reaction products was determined. Nitrogen was substituted for secondary air in one experiment, and in another the suppression of smoke by a turbulent secondary-air stream was also investigated.

APPARATUS

A benzene-air combustible mixture was used for all the work described herein. Redistilled benzene was metered to a mixing tube from a burette by means of a glass capillary 50.0 centimeters in length and 0.05 centimeter in internal diameter (fig. 1). A capillary bleed was connected between the mixing tube and the base of the burette to provide a constant pressure head over the capillary. A screw clamp was kept on the tubing bypass of the capillary bleed until pressure equilibrium was established. When the pressure equilibrium was reached, the screw clamp was loosened, and the benzene was discharged at a constant rate for a given temperature. Deviation in flow rate was not observed at the different benzene levels in the burette. The flow rate was determined by making a time-volume tabulation of the benzene level in the burette. Filtered air from the service-air line was metered to the mixing tube through a calibrated flowmeter. The mixing tube, or evaporator manifold, is shown in figure 1. The benzene from the capillary flowed down the inclined bottom of the manifold tube and evaporated into the metered air until an equilibrium was established. All the benzene evaporated before it reached the bottom of the manifold. Such a system exhibits an appreciable equilibrium lag, but has the advantages of excellent stability once equilibrium is established. A series of different constant flow rates was obtained by inserting wires of different lengths into the capillary to reduce the flow.

The burner, shown in figure 1, was used to heat the fuel-air mixture to various temperatures up to 450°C . The inner pyrex burner tube was wrapped with Nichrome wire the temperature of which was controlled by means of an ammeter and a variable-voltage transformer. A glass sleeve separated the windings from the magnesia insulation, and a roll of copper gauze served as a flame trap in the base of the burner.

The burner was modified for study of the effects of chimneys, or shrouds, as shown in figure 2. The burner tube was extended several inches above the top base plate and sealed in place with a ceramic cement. Nine chimneys were cut from pyrex tubing; tubes having internal diameters of 1.8, 2.8, and 3.8 centimeters were each cut into 12.5-, 25-, and 50-centimeter lengths.

The influence of secondary air on flame-smoking characteristics was studied in the simple duct shown in figure 3. The fuel-air mixture was burned on a central pyrex tube. A secondary-air sleeve was fitted around the burner tube, and the assembly was inserted into a 2.8-centimeter inside-diameter pyrex tube. Burner tubes having internal diameters of 0.6, 0.7, and 0.9 centimeter were interchangeable in this system. Either air or nitrogen could be introduced into the secondary-air sleeve. When all secondary air was shut off, the flame separated and the carbon monoxide diffusion flame burned at the mouth of the duct; a chimney was used to stabilize the carbon monoxide flame.

PROCEDURE

Carbon-Forming Point and Smoking Point

Preliminary studies of the benzene-air flame showed that as the fuel-air ratio was made progressively richer than stoichiometric, a point was reached at which a tiny yellow pip of incandescent carbon formed in the flame tip of the inner cone. Progressive increases in the fuel percentage caused this tip to lengthen into a spike of incandescent yellow that gradually extended to the limits of the outer cone and then expanded and spread downward over the inner cone until a flame similar in appearance to a diffusion flame was formed. This completely yellow-colored flame then lengthened and finally smoked as the fuel percentage was increased still further. The experimental data reported herein were taken at two points: (a) at the fuel-air ratio at which the pip of incandescent carbon first became visible in the flame and (b) at the fuel-air ratio at which the flame started to smoke. These points will be called the carbon-forming point and the smoking point of the flames.

Chimney Variation

The position and size of the chimney affected the smoking point; and the burner was therefore modified as shown in figure 2 to determine the effect on the carbon-forming point and the smoking point of nine glass-tubing shrouds used as chimneys for the flames. These shrouds were alined coaxially with the burner tube, with the chimney base 2.5 centimeters below the burner port.

The middle sized chimney, 2.8 centimeters in diameter and 25.0 centimeters long, was selected for use in determining the effect on the carbon-forming point and the smoking point of variations in the chimney-base position. This chimney was alined with its base at several

stations, 1/2 inch apart, above the burner base plate. Room-temperature determinations of the carbon-forming point and the smoking point were made with the chimney at each station.

Temperature Measurement

The fuel-air mixture was passed through the burner tube, ignited, and adjusted to the carbon-forming-point fuel-air ratio. The voltage to the Nichrome heating element around the burner tube was set at a predetermined value and the burner was allowed to come to a temperature equilibrium. Inasmuch as the fuel-flow rate was constant, the fuel-air ratio was adjusted by adjusting the air-flow rate to keep the flame at the carbon-burning point as the initial gas temperature was increased. Periodically the flame was blown out and the gas temperatures were measured with a chromel-alumel thermocouple inserted 5 centimeters into the top of the burner. When temperature equilibrium was reached, the flame fuel-air ratio was critically adjusted at the carbon-burning point and measurements of fuel-flow rate, air flow rate, and gas-mixture temperature were made. This procedure was followed for a series of temperatures from 28° to 450° C. The fuel-air ratio was then set at the smoking point and the same procedure was repeated for the same temperature range. The flame at its smoking point was easily disturbed by stray air currents. It was found that the flame motion could be reduced by placing a chimney above the flame. All data on flame carbon-forming points and smoking points at elevated temperatures were obtained with a chimney, 3.8 centimeters in diameter and 12.5 centimeters long, suspended coaxially 5.0 centimeters above the burner nozzle.

Fuel-Flow Variation

The capillary tube of the benzene meter shown in figure 1 was 50 centimeters long. A wire somewhat less in diameter than the capillary was cut into lengths that were multiples of 5.0 centimeters. By using wires of various lengths from 15 to 50 centimeters, a fuel-flow range of constant values ranging from 0.19 to 0.60 milliliter of benzene per minute was obtainable. At higher fuel flows the benzene would not evaporate completely upon passage through the manifold. The carbon-forming point and smoking point for a range of fuel flows was measured at 28° and 450° C in the burner tube.

Ducted Burner

A benzene-air flame was burned in a duct as shown in figure 3 to determine the effect of secondary-air-flow rate on the carbon-forming point and smoking point in benzene flames. A flame was ignited on the inner tube and metered secondary air was passed around the flame from the secondary-air tube. The flow of secondary air was set at several constant values and the carbon-forming and smoking points of the central benzene-air mixture were determined. These experiments were repeated with burner tubes having internal diameters of 0.6, 0.7, and 0.9 centimeter. The carbon-forming and smoking points were also measured when nitrogen was substituted for secondary air, and when no secondary air was metered into the duct. In the latter case, the flame separated and a carbon monoxide diffusion flame burned on the end of the duct. Finally, the flowmeter on the secondary air was disconnected and service air was directly introduced as secondary air at a rate of flow sufficiently high to be turbulent. The carbon-forming and smoking points were determined for this condition.

RESULTS AND DISCUSSION

Influence of Chimneys

The influence of chimney length and diameter on the smoking point is shown in figure 4. The effect of variation in chimney position on the smoking point is shown in figure 5. The use of the chimneys gave varied results that depended on convection in the chimneys. In general, all chimney variables which improved the smoke-burning characteristics did so by generating a flue effect which tended to sweep away the sheath of hot gases and flow air around the outer cone. The enhanced diffusion of oxygen resulting from this effect increased the smoking-point fuel-air ratio. The chimneys had no effect on the carbon-forming point (figs. 4 and 5).

Influence of Initial Mixture Temperature

The Bunsen cone generates a sheath of hot gaseous combustion products through which oxygen from the surrounding air must diffuse in order to react with the incandescent carbon. Those variables which improve the diffusion of oxygen through this zone should improve the smoke-burning characteristics of the flame. The rise in initial gas-mixture temperature caused no change in the smoking point (fig. 6). In this instance it is probable that the enhanced diffusion rate due to the hotter gases was compensated for by the greater diffusion-path length resulting from increased gas expansion. The fuel-air ratio at which the yellow pip of incandescent carbon first appeared in the flame was

remarkably resistant to any influence other than temperature. A range of conditions ranging from no secondary air at all to a rapidly sweeping and mixing turbulent secondary-air stream caused no visible change in the carbon-pip size when the fuel-air ratio was set for the carbon-forming point at a given temperature. As the temperature was varied, however, the percentage stoichiometric fuel-air ratio at the carbon-forming point varied from approximately 140 percent at 28°C to approximately 162 percent at 450°C (fig. 6). It is probable that the 450°C thermocouple-temperature reading was somewhat low, inasmuch as a slight increase in furnace temperature above an indicated 450°C caused the fuel-air mixture to ignite in the burner tube. The spontaneous-ignition temperature of benzene is reported as 588°C in reference 2, but this value was measured in a different type of apparatus.

The low value for the carbon-forming point at room temperature (140 percent of stoichiometric) might be explained on the basis of the preferential diffusion of the lighter nitrogen and oxygen molecules away from the rounded tip of the flame front (reference 3). This diffusion would result in a richer fuel-air ratio at the flame tip than that which exists in the bulk of the mixture. Higher temperatures may enhance pyrolysis of the hydrocarbon, and the greater diffusion rate of such products may bring the fuel-air ratio of the flame tip in line with the over-all fuel-air ratio of the gas mixture.

Although the coincidence may be fortuitous, stoichiometric calculations for the reaction of benzene and oxygen reveal that complete conversion of water and carbon monoxide could be accomplished at a fuel-air ratio 167 percent of stoichiometric. If the usual small cumulative experimental errors were compensated for, it might be found that the first formation of luminous carbon in the flame tip occurred at 167 percent of stoichiometric.

Influence of Fuel-Flow Rate and Flame Length

Increased fuel-flow rate lengthened the flame, but decreased the fuel-air ratio at the smoking point (fig. 7). The geometry of the burning flame was probably responsible for the decrease in the fuel-air ratio at the smoking point for the longer flames. As a cone with a constant diameter base increases in length, its surface-to-volume ratio decreases. Since less surface in proportion to the volume of reactants is available in the longer flames, less oxygen diffuses into the outer cone and the smoking-point fuel-air ratio decreases.

Influence of Secondary Air

If the surrounding air supply was gradually withdrawn from the flame, or if nitrogen was substituted for secondary air, the percentage stoichiometric fuel-air ratio at the smoking point dropped until as all the air was withdrawn, the flame disintegrated at a fuel-air ratio of approximately 164 percent of stoichiometric (fig. 8(a)). At a given secondary-air-flow rate, the fuel-air ratio at the smoking point decreased as the fuel-flow rate increased (fig. 8(a)).

When benzene flames are burned without secondary air, either in a nitrogen atmosphere or as a separated flame burning in its own reaction products so that no oxygen other than that in the original mixture is available, the carbon pip expands rapidly into the outer cone at fuel-air ratios much above 140 percent stoichiometric. If preferential diffusion of oxygen occurs at the flame tip, as discussed previously, this diffusing oxygen in the outer cone may be assumed to recombine with the incandescent carbon to form carbon monoxide rather than carbon dioxide inasmuch as no smoke escapes from the flame up to fuel-air ratios of approximately 164 percent of stoichiometric. (This amount of oxygen would allow only 50 percent conversion to carbon dioxide.) There is evidence that carbon burns first to carbon monoxide and then to carbon dioxide (reference 4). It would appear that there is a critical value of fuel-air ratio for benzene below which no smoke formation is possible, regardless of the conditions in the surrounding gas. This value is approximately 164 percent of stoichiometric. Once the critical fuel-air ratio is exceeded, excess carbon exists in the flame. This carbon can be burned only if oxygen from the air surrounding the flame diffuses into the outer cone and reacts with the incandescent carbon. The amount of carbon that can be burned in the outer cone varies greatly with the conditions in the gas surrounding the flame. At an initial gas temperature in the burner of about 500° C, and in the absence of secondary air, no appreciable amount of carbon can exist in the flame. This fact is confirmed by comparison of the carbon-forming-point and smoking-point fuel-air ratios in figures 6 and 8. The critical fuel-air ratio cannot be exceeded without destroying the flame.

The majority of the experimentation reported herein was concerned with laminar-flow flames surrounded by either still air or by laminar-flow secondary air. The initial fuel-air ratio of the mixture is assumed to exist up to the reaction zone. The only contribution of the secondary air is assumed to be the supplying of oxygen which diffuses into the outer cone and reacts with the incandescent carbon. Thus, all smoking data in this report are based on the primary fuel-air ratio of the gas mixture issuing from the burner tube. If the secondary air is turbulent, turbulent mixing, as well as diffusion, occurs in the outer cone. The relations of initial fuel-air ratio and oxygen diffusion to

the smoking of flames as found for laminar flow secondary air do not hold for turbulent secondary-air flow. The turbulent secondary air mixes with the outer cone and dilutes it until the flame burns with only a trace of carbon visible even with almost 100 percent fuel in the primary-gas mixture.

Influence of Burner-Tube Diameter

The use of the large burner-tube diameters resulted in smoking points at lower fuel-air ratios (fig. 8(b)). These data are replotted in figure 8(c) for three secondary-air-flow rates. The large diameter burner tube had a short flame because of the constant mass flows in the three tubes. The flame diameter was also large, and the flow rate low in the large tube. These factors tended to make the outer cone stubbier and thicker than would be the case with high gas flow in flames on smaller burners. The thicker cone might inhibit diffusion and result in lower smoking-point fuel-air ratios.

SUMMARY OF RESULTS

Benzene-air mixtures were burned as Bunsen flames on burner tubes less than 1 centimeter in diameter. The flames were made progressively richer over a range of initial gas temperatures, fuel-flow rates, flame lengths, secondary-air-flow rates, and burner-tube diameters. The following changes were observed in the fuel-air ratio at which the yellow incandescence indicative of burning carbon first appeared in the flame, and in the fuel-air ratio at which the flame smoked:

1. The fuel-air ratio at which incandescent carbon first appeared in a benzene flame varied from a value of about 140 percent of stoichiometric at 28° C to approximately 162 percent of stoichiometric at 450° C. No other variable measured had any effect on this carbon-forming-point fuel-air ratio.

2. The fuel-air ratio at which benzene flames smoked did not vary as initial gas temperatures were changed from 28° to 450° C; this was the only variable measured that did not affect the smoking-point fuel-air ratio.

3. The fuel-air ratio at which smoking occurred decreased as the fuel-flow rate was increased although the flame length at the smoking point increased.

4. At a given secondary-air-flow rate, the fuel-air ratio at the smoking point decreased as the fuel-flow rate increased.

5. The fuel-air ratio at the smoking point decreased as the secondary-air-flow rate was decreased in a duct containing the benzene flame. As the secondary-air-flow rate approached zero in the duct, the fuel-air ratio approached approximately 164 percent of stoichiometric at the smoking point.

6. With the secondary air replaced by nitrogen or with no secondary air, the flame remained stable up to a fuel-air ratio of approximately 164 percent of stoichiometric. Above this fuel-air ratio the flame separated and disintegrated.

7. As the secondary-air velocity was increased into the turbulent regime, the flame mixed with the turbulent air until even flames of the richest primary fuel-air ratios were made lean enough to burn without smoking.

8. When the fuel-flow rate was held constant at a given secondary-air-flow rate, the fuel-air ratio at smoking decreased as the burner diameter increased.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

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4. Mertens, E., and Hellinckx, L.: Mechanism of Carbon Combustion. Third Symposium on Combustion, Flame and Explosion Phenomena. The Williams and Wilkins Co., Baltimore (Maryland), 1949, pp. 474-475.

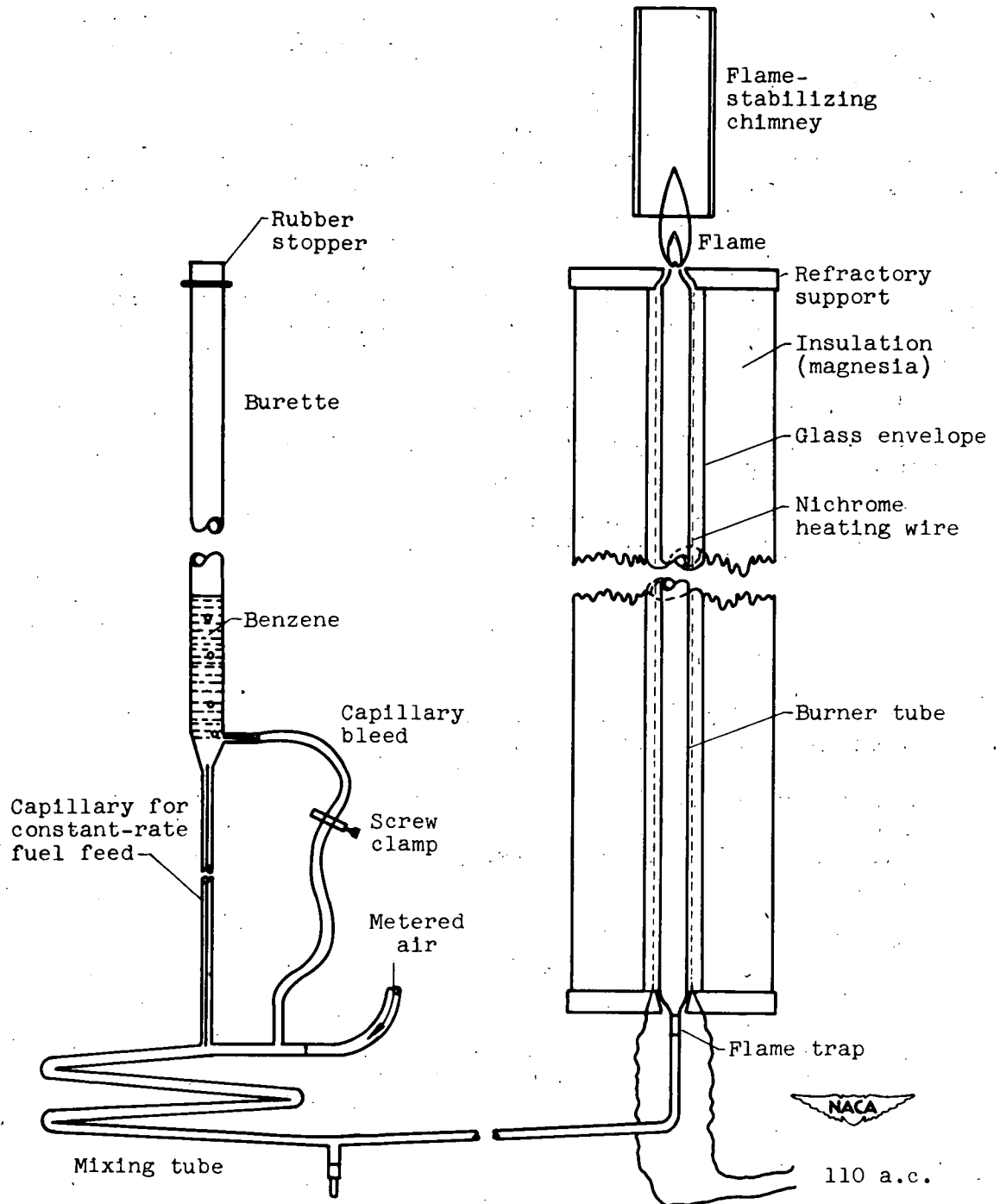


Figure 1. - Schematic diagram of benzene-air mixer and burner tube.

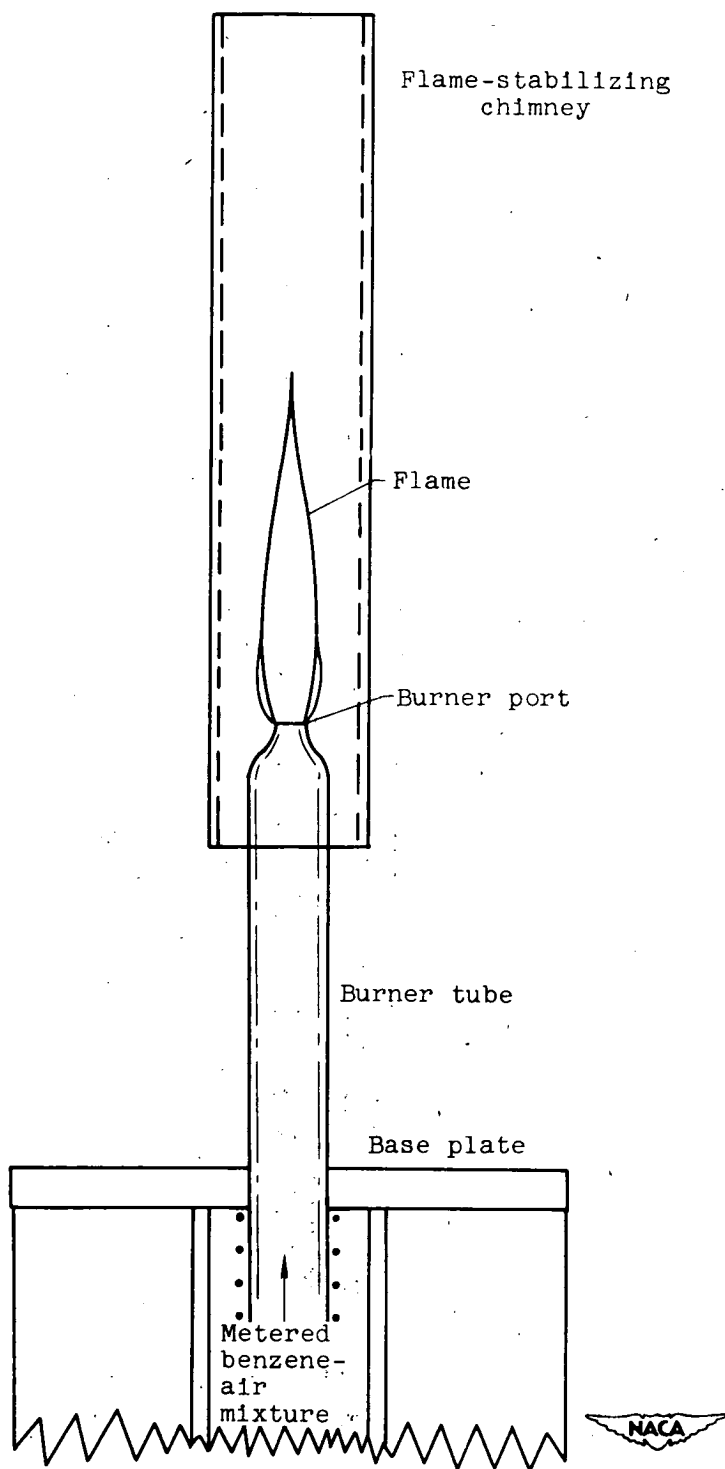


Figure 2. - Modifications to burner tube for studying influence of chimneys.

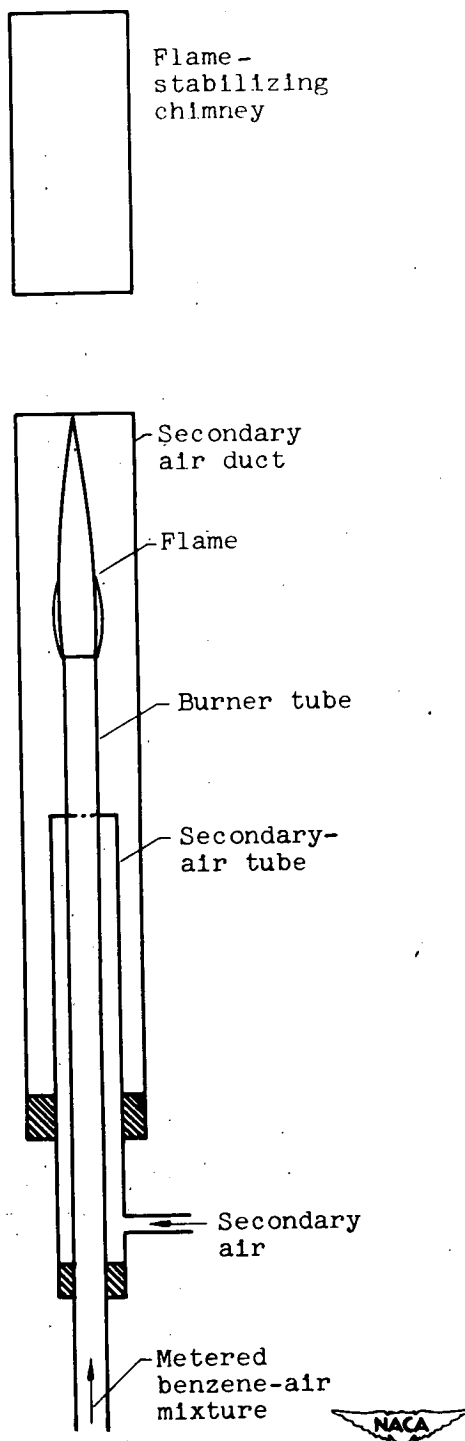


Figure 3. - Diagram of apparatus used to study influence of secondary air on smoking of benzene flames.

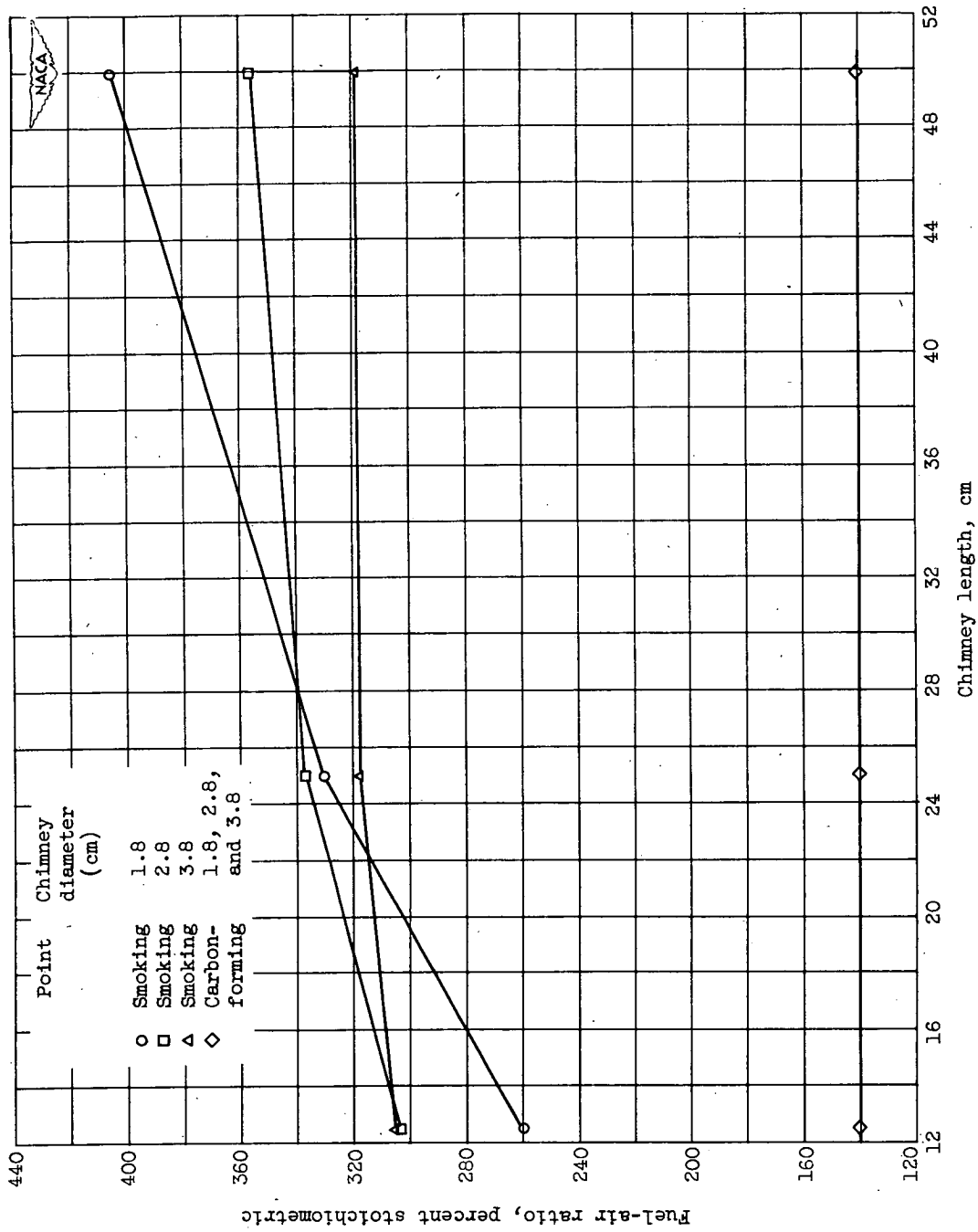


Figure 4. - Influence of chimney length and diameter on carbon-forming and smoking points of benzene-air flames.

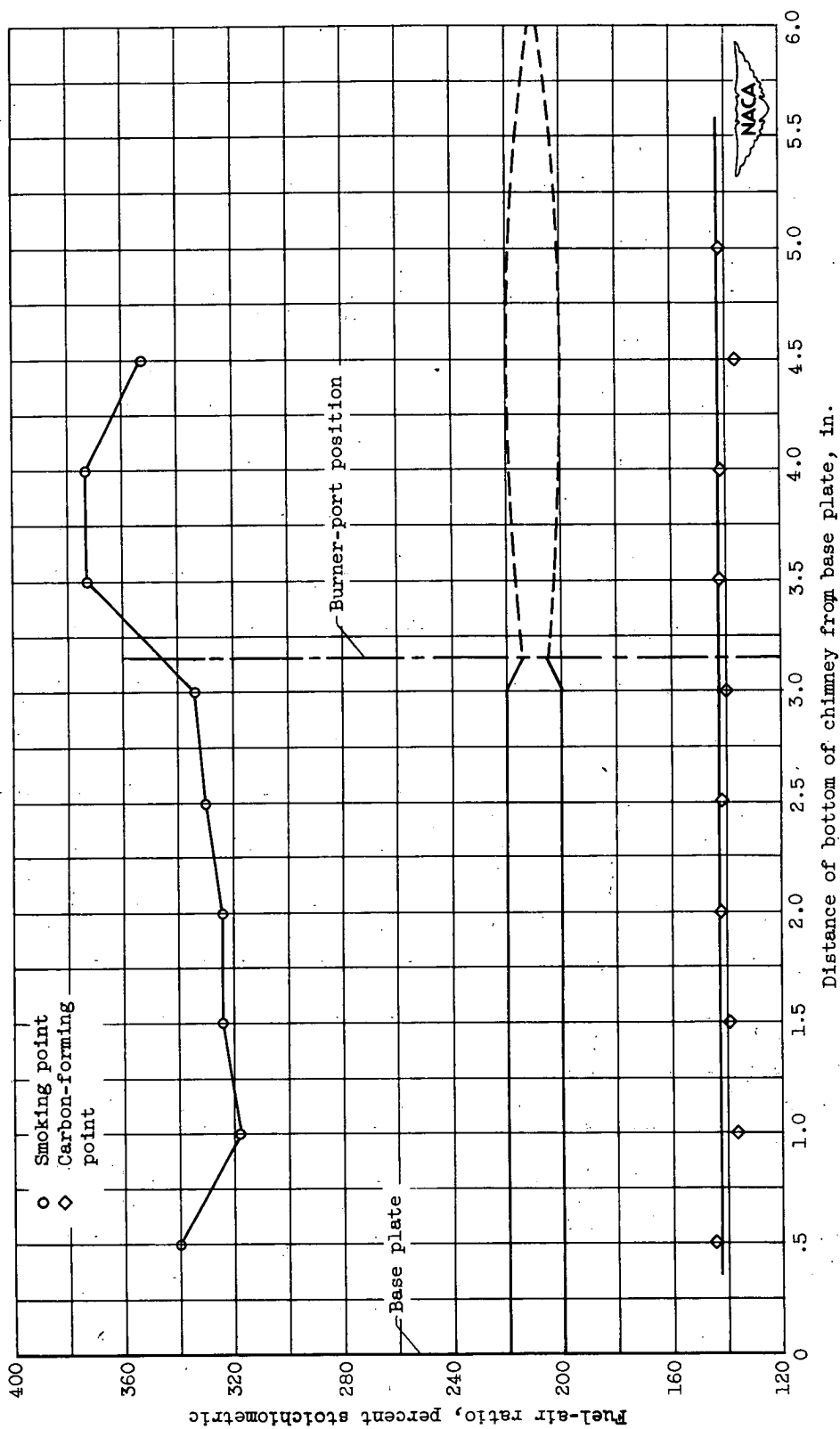


Figure 5. - Influence of chimney-base position on carbon-forming and smoking points of benzene-air flames in 2.8 by 25 centimeter chimney.

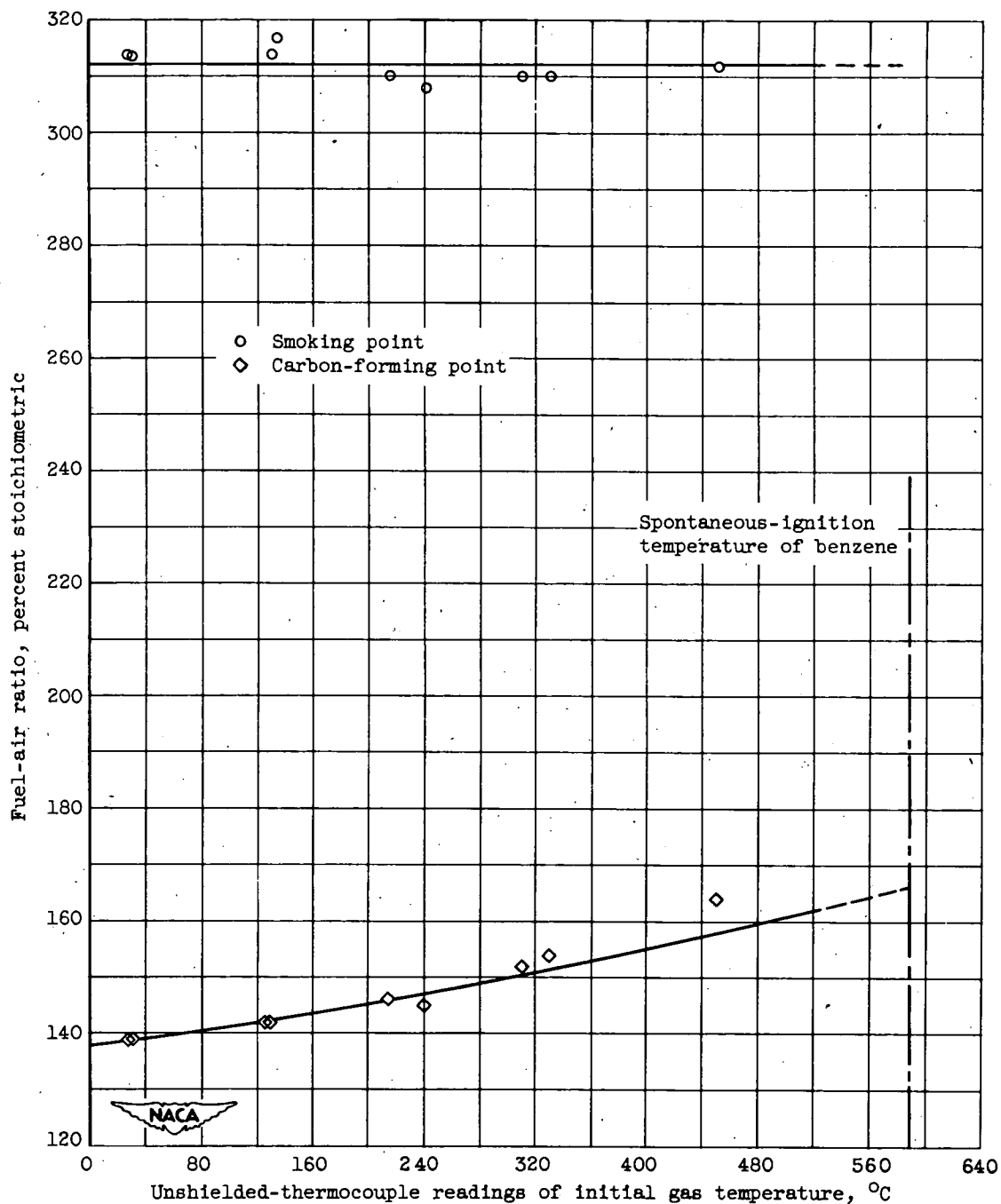


Figure 6. - Variation with temperature of fuel-air ratio at carbon-forming and smoking points of benzene-air flames.

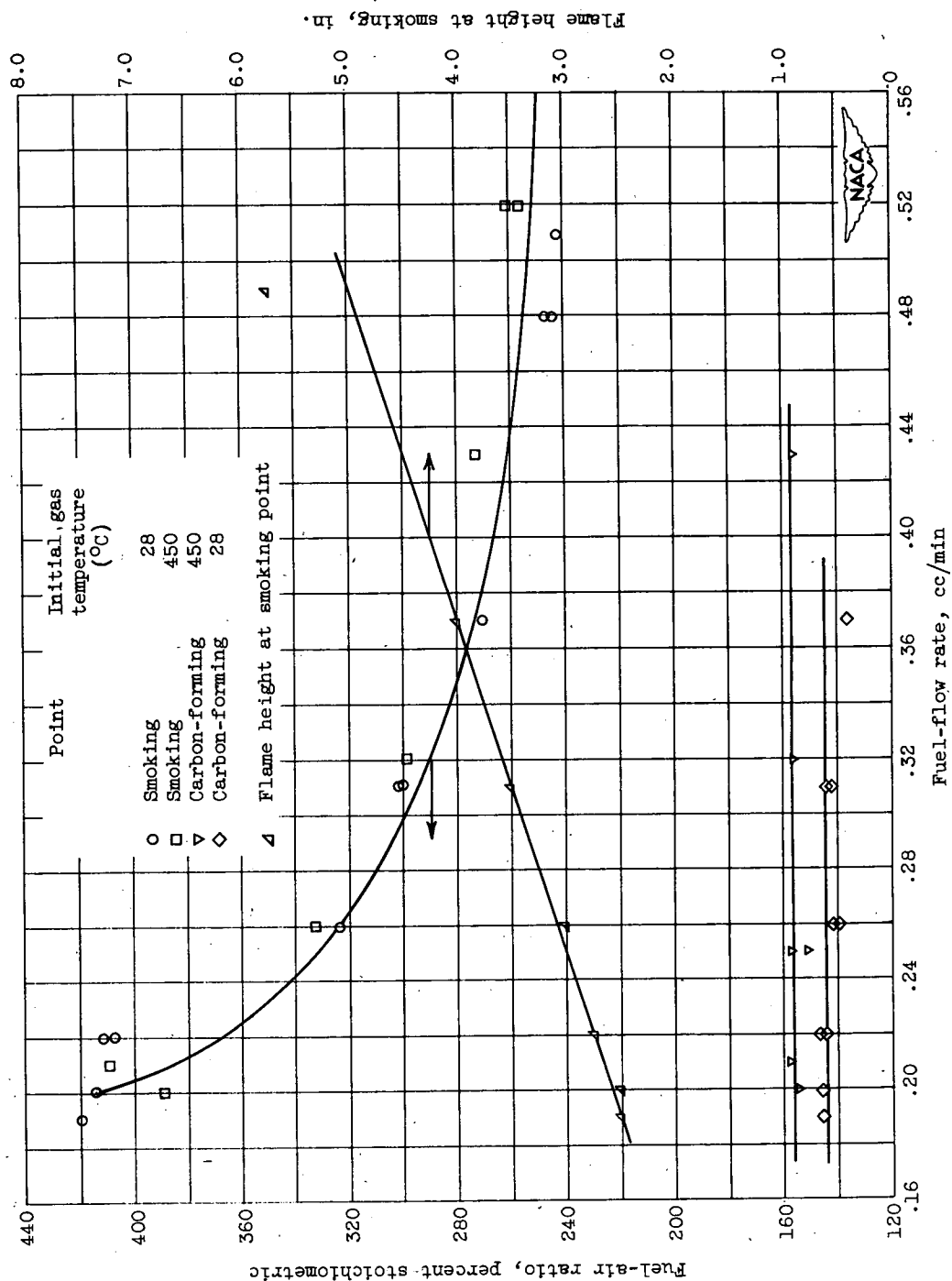


Figure 7. - Variation of flame height and fuel-air ratio with fuel-flow rate at carbon-forming and smoking points of benzene-air flames. Fuel, liquid benzene.

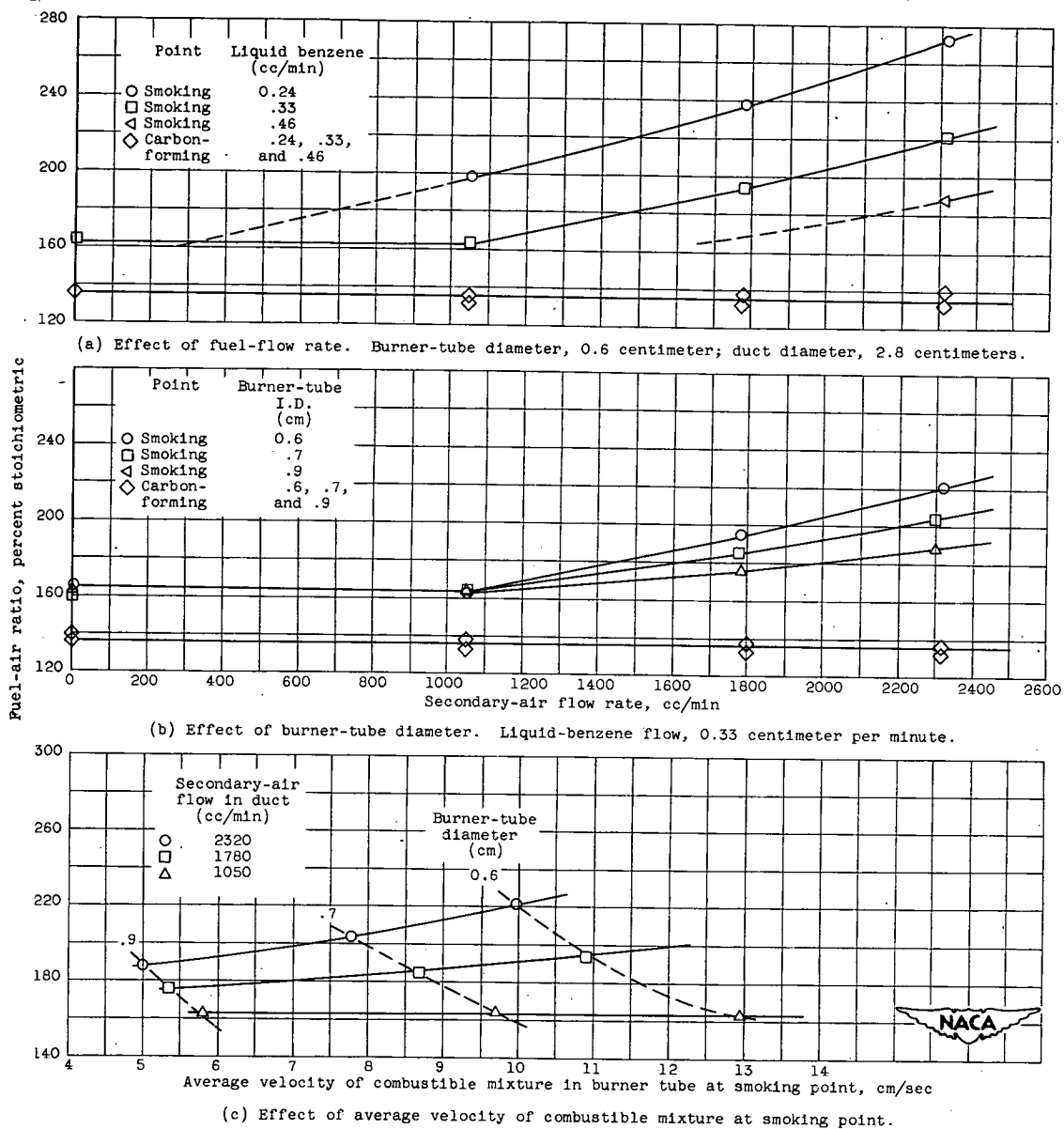


Figure 8. - Influence of secondary-air flow rate on carbon-forming and smoking points of benzene-air flames.